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A SMALL, 1400° K, REACTOR FOR BRAYTON SPACE POWER SYSTEMS

by Edward Lantz and Wendell Mayo
Lewis Research Center
Cleveland, Ohio

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Lewis Research Center
National Aeronautics and Space Administration
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I. INTRODUCTION

One reason nuclear reactor systems are not presently being used in space is because they are too big and heavy. Yet, the need for power in space is rapidly approaching the point where more expensive systems such as large solar cell-battery systems or large radioactive thermoelectric generators will be used if competitive nuclear reactors are not developed. This would be wasteful in the long run.

Some possible, small, high-temperature reactors for space were discussed in Ref. 1. Since it was written, two technologies are starting to come to fruition which if now used could lead to a significant decrease in the size, weight, and cost of an advanced space power reactor system. The two technologies are: (1) The development and testing of a tantalum alloy (T-111) clad uranium nitride (UN) fuel element which is discussed in Ref. 2. (2) The development of production and handling methods for uranium 233 (U^{233}) fuel elements. These are being fabricated for the Light Water Breeder Reactor (LWBR) as discussed in Refs. 3 and 4. An alternative to the U^{233} fuel would be Pu^{239}, the nitride of which has been developed by Battelle Columbus and ORNL (refs. 5 and 6).

This study was done to determine how small and light a reactor could be with $U^{233}N$ or $Pu^{239}N$ as the fuel in the T-111 fuel elements of the reactor design described in Ref. 7. The design of the fuel elements, which are being tested in the Plumbrook Reactor, was not changed in any way,

nor was the basic reactor design, even though some changes could be made to make the reactor even smaller.

The Brayton cycle can attain system efficiencies up to about 30 percent. This is considerably higher than the efficiencies of other conversion systems. Due to this higher efficiency the criticality limit for a minimum sized reactor penalizes the Brayton system more than less efficient conversion systems at low power levels. Thus more reactive fuels for the Brayton system allows a lower power level with a significant decrease in reactor weight and size.

II. PRESENT SPACE POWER STATUS

At the present time solar cell-battery systems are the main source of electricity in space, but Radioactive Thermoelectric Generators (R. T. G.'s) are being used for some missions. However, these are expensive systems. Solar cell systems presently cost about one million dollars per kilowatt of electricity (ref. 8). And R. T. G.'s, due to the price of plutonium-238, cost about fifteen million dollars per kilowatt of electricity (ref. 9). At these prices, as shown on Fig. 1, it should be possible for nuclear reactors to become cost competitive at a power level of a few kilowatts. However, as also shown in Fig. 1, the specific weight of the presently planned zirconium hydride reactors may not be competitive with future solar cell sysems especially for manned missions. Thus we should continue to search for better nuclear reactor systems. One of the heavier components in the reactor system is the radiator. But the zirconium hydride reactors have a maximum temperature of about 920° K (1200° F) for which about 50 ft^2 of radiator area is required for every kilowatt of net electricity.

The advanced reactor must lead to a system which is considerably superior to the present systems in order to justify development cost.

One way of reducing the required radiator area is to increase the operating temperature. For a 1420° K (2100° F) Brayton system operating at 25 percent efficiency the 50 ft^2 for the zirconium hydride reactor could be reduced to about 15 ft^2. This is over a factor of three reduction. Also,

as will be seen, even though refractory metal, fast spectrum reactors tend to be heavier than zirconium hydride reactors, the fast spectrum reactors have a potential for a much greater power density. Thus the specific weight (lb/kw) of fast spectrum reactors can be considerably less.

III. U^{233} OR Pu^{239} AS SPACE REACTOR FUEL

For the past five years there has been a great reluctance to consider either U^{233} or Pu^{239} as the nuclear fuel for space reactors. The main objections are their radioactivity, unavailability, and questionable controllability in a fast spectrum reactor. These are discussed in the following sections.

Radioactivity

The main impetus for considering U^{233} rather than Pu^{239} is that a major part of the material development could be done with the easier to handle U^{235}. Presumably that switch to U^{233} could be made after all of the materials and fabrication processes were well tested and after the fuel elements had been irradiation proof tested with U^{235}.

According to Ref. 10, U^{233} with U^{232} impurity does not have the spontaneous fission that plutonium has, and its hazard value for contamination control and for internal emitters is in the intermediate group. Plutonium on the other hand is in the very hazardous group. The γ rays of the daughters of U^{232} build up over a ten year period. These radioactive daughters can be chemically separated from the U^{233} at any time, but from ten days after separation until ten years after separation, when equilibrium is reached, the γ activity increases by a factor of about 200.

The fuel element design that is now being tested in the Plumbrook Reactor is shown in Fig. 2. The fuel pellets are 0.75 in. (1.91 cm) in diameter and there is 14.8 in. (37.6 cm) of fuel in each element. The

clad is 0.058 in. (0.15 cm) thick T-111 with a 0.005 in. (0.013 cm) tungsten liner. T-111 is a tantalum alloy with about 8 percent tungsten and 2 percent hafnium. The average fuel mass in one of these elements is 0.83 kg.

Figure 3 shows the dose rate in millirads per hour at one foot from the fuel element for both plutonium and U^{233} fuel. The plutonium is production material which is 93.5 percent Pu^{239}, 6 percent Pu^{240}, and 0.5 percent Pu^{241}. The U^{233} has seven parts per million U^{232}. These curves were drawn from data given in Ref. 10. The upper curves labeled "Total" are for the bare nuclear fuel. These include the α and β radiation. The 0.063 in. (0.16 cm) clad will totally attenuate all of the α and β radiation so only the γ will be present once the fuel is sealed inside of the fuel element. This is shown on the lower curves. Since the dose rate permitted under A.E.C. regulations is 1.25 rem (1250 mrem) of whole body radiation or 18.75 rem (18 750 mrem) to the hands per quarter year, and for γ rays the relative biological effectiveness (R.B.E.) is one, it is seen that a few millirad per hour is a low level of radioactivity and can be easily accommodated. Ten days after separation a U^{233} with 7 ppm U^{232} fuel element would be generating about 3 millirads per hour. Ten years after separation, when the radioactivity is a maximum, this U^{233} fuel element would be generating about 0.6 rads per hour. So from a convenience of handling standpoint it would be better to use the U^{233} as soon as possible after separation even though it would be possible to handle it for a short period of time even after ten years.

A fact to note about the radioactivity of a nuclear fuel for space power is that Pu^{238} is presently being used in space. And it is considerably more radioactive than unclad Pu^{239}.

There can be no doubt that these relatively small fuel elements with U^{233} in them can be made. According to Ref. 3 the fuel elements for the Light Water Breeder (LWBR) contain Uranium 233 oxide and thoria ($U^{233}O_2$ and ThO_2) and are about eight and one half feet long. And according to Vice Admiral H. G. Richover's testimony in Ref. 4:

"In fiscal year 1972 we expect to get production of fuel elements going on a large scale and start assembling core parts in subassemblies."

Availability

For the small space power reactors considered here both the plutonium and U^{233} fuels are now available. Since according to Ref. 11 every large (800-1000 MWE) light water reactor generates from 150 to 200 kilograms of fissile plutonium annually there is a guaranteed future source of plutonium.

In December of 1970 the price of plutonium became uncertain because the A.E.C. ended the guaranteed plutonium buy back. But Ref. 11 estimates the future price to be about $8 per gram. This is less than the present price of 93 percent enriched U^{235}, and about 30 times less than the cost of Pu^{238} which is presently being used in space. According to the A.E.C. Division of Production and Materials Management there are many hundreds of kilograms of U^{233} in inventory and there is several hundred kilograms available now with the U^{232} content in the seven part per million range. Since all that will be required for this reactor is about fifty kilograms there certainly should be enough 7 ppm material now available for two core loadings.

Reactivity Control

The controllability of a fast spectrum reactor which has U^{233} or Pu^{239} as the principal nuclear fuel is another often mentioned concern. This is primarily because of the smaller delayed neutron fraction of these fuels. These are compared with that of U^{235} in Fig. 4, which was taken from Ref. 12. From this it is seen that the delayed neutron fraction, β, for both of these fuels is about one third that for U^{235} and thus the transient responses of Pu^{239} and U^{233} fueled reactors should be similar. The primary effect of the lower β is to increase the reactivity sensitivity of a given

control device. So this means that either the control device must be more precisely positioned or more devices used which have less worth per control increment. But since it is relatively easy to make very small control devices, this presents no fundamental problem.

Direct comparison studies were made between the reactor kinetics of a U^{235} reactor and an equivalent U^{233} reactor and reported in Refs. 13 and 14. In Ref. 13 it was found that for up to a maximum positive reactivity input of \$10 a safe reactivity input rate is 3 cents per second in a U^{233} reactor whereas it would be about 20 cents per second in a U^{235} reactor. And in Ref. 14 it was found that a U^{233} reactor could have more reactivity overshoot in terms of dollars than an equivalent U^{235} reactor.

IV. REACTOR DESCRIPTION

Figure 5 is a conceptual drawing of the reactor which was studied. The basic design of this reactor was taken to be the same as described in Ref. 7 except the number of fuel elements has been reduced from 247 to 61. This allowed the overall diameter to be reduced from 22-7/8 in. (58 cm) to 14 in. (35.6 cm) which reduces the reactor weight from about 3200 lb (1450 kg) to less than 900 lb (408 kg); assuming the reflectors to be made entirely of molybdenum alloy (TZM). Yet, this is still not a minimum size reactor. It is not a close packed configuration but has a T-111 honeycomb, which essentially isolates each individual fuel element and provides a uniform 0.102 cm (40 mil) wide coolent channel around it. This design, is conservative from a heat transfer and fuel element bowing standpoint, but it is probably larger than a design without a honeycomb.

Figure 6 shows the calculated neutron multiplication factors for this reactor with U^{233} nitride and Pu nitride fuel with molybdenum and tantalum beryllide (Ta_2Be_{17}) reflectors. Two dimensional Sn calculations were made in cylindrical plane (R-θ) geometry with S_4 quadrature and P_0-13 group cross sections. Two geometries were used. One with the fuel elements in the control drums turned full in toward the stationary core the other with the fuel turned full out.

It was assumed that all six control drums were rotated in the same direction. All calculations included a lithium hydride shield around the 14 in. (35.6 cm) pressure vessel. From the calculated numbers for U^{233} the attainable reactivity control swing is

$$\text{Attainable control swing} = \frac{1.073 - 0.951}{0.951 \times 1.073} \times 100 = 12\%$$

Figure 7 shows the reactivity requirements. The reactivity required to get the reactor from room temperature up to 2200° F (1480° K) consists of that needed for core expansion, the lithium-seven coolant expansion, and the integrated Doppler. These will add up to about 1.7 percent $\Delta k/k$. In order to generate 445 kilowatts of thermal energy for 44 000 hours will require reactivity to compensate for the fuel that is destroyed, and the axial fuel swelling with fission product build up. These will add up to about 1.9 percent. Since these are preliminary numbers some contingency is required. This is assumed to be 0.5 percent $\Delta k/k$. Also the difference between our calculated neutron multiplication factor and that obtained in heavy-metal-reflected, fast spectrum experiments has been about 3 percent $\Delta k/k$; so this number was used. This gives a total reactivity requirement of 7.1 percent $\Delta k/k$. Comparing this with the calculated multiplication factors given on Fig. 6 shows that this reactor should have enough reactivity.

Figure 8 shows the total reactivity control requirements where it is assumed that it should be possible to shut down the reactor by 1 percent with two adjacent control drums stuck in their most reactive positions. For this capability with six control drums:

$$\left(\frac{\Delta k}{k}\right)_{\text{excess}} - \frac{2}{3}\,(\text{Total control swing}) = -1\%$$

and since

$$\text{Total control swing} = \left(\frac{\Delta k}{k}\right)_{\text{excess}} + \left(\frac{\Delta k}{k}\right)_{\text{shutdown}}$$

$$\left(\frac{\Delta k}{k}\right)_{\text{shutdown}} = \frac{\left(\frac{\Delta k}{k}\right)_{\text{excess}}}{2} + 1.5$$

From this for $\left(\frac{\Delta k}{k}\right)_{\text{excess}} = 4.1\%$

$$\left(\frac{\Delta k}{k}\right)_{\text{shutdown}} = 3.55\%$$

However, this must have a contingency allowance and also a factor for the interaction between two adjacent control drums. Allowing 0.5 percent for each of these gives the $(\Delta k/k)_{\text{shutdown}} = 4.6\%$ as shown on Fig. 8 and also the consequent total swing of 8.7 percent. Since our calculations showed that 12 percent was attainable, it may be possible to reduce the size of the control drums or at least move some fuel out of the drums into some low power fuel elements in the stationary part of the core.

For a total control swing of 8.7 percent the individual control drum worth will be 1.45 percent. This is for 180 degrees of rotation. Thus assuming only one drum is stepped at a time the average reactivity per degree of drum rotation will be

$$0.0145 \times \frac{100¢}{0.0026} \times \frac{1}{180^{o}} = \frac{3.1¢}{\text{Degree}}$$

As shown by the control curve on Fig. 9 the peak sensitivity will be somewhat higher, but it still should be easy to limit the reactivity insertion rate to 3 cents per second as suggested by previous kinetic studies for a U^{233} reactor. Either the allowable step rate can be limited to less than one per second or the step increment can be limited to somewhat less than one degree.

Figure 10 shows the power distributions in this reactor. The axial distribution will be a chopped cosine shape with a peak to average value of about 1.23 as calculated in Ref. 15. The radial power distribution as obtained from the aforementioned R-θ calculations is shown in the 60 degree sector of the core. The numbers given are the average power densities in each of the fuel elements. According to Ref. 16 a fuel element with a fuel volume fraction of 0.42 cannot have a beginning of life (BOL) radial power ratio greater than one in order to achieve 50 000 hours and not exceed 1.0 percent diametrical creep with the present clad. But this core was designed for 2.17 megawatts thermal for 50 000 hours. So for a peak radial power ratio of 1.21 with a fuel volume fraction of 0.42 the core power for 44 000 hours will be limited to

$$\left.\begin{matrix}\text{Allowable Core Power} \\ \text{from Swelling Limit}\end{matrix}\right\} = 2.17 \text{ Mwth} \times \frac{61}{247} \times \frac{1.0}{1.21} \times \frac{50\,000}{44\,000} = 0.505 \text{ Mwth}$$

Also from Ref. 16 it can be seen that the fuel elements with a beginning of life power ratio of 1.3 and a fuel volume fraction of 0.377 are not as limiting as the above element.

The assumed heat transfer rate from the fuel elements of the 247 element reactor was very conservative. The average value was only 40 W/cm^2. If this same limit is kept for this reactor the power would be limited to

$$\frac{61}{247} \times 2.17 = 0.535 \text{ Mwth}$$

but this is larger than the swelling limit of 505 kilowatts thermal set by one percent clad creep so it is really not a limit. This creep limit was for a reactor with a lithium outlet temperature of 1800° F (1143° K). Calculations by Harry Davison of this Center show that if the operating temperature is raised to where the lithium outlet temperature is, 2060° F (1400° K), the lifetime will be decreased to about 20 000 hours for the one percent creep limit. For 450 kwth a somewhat longer life could be expected.

Figure 11 shows the material volume fractions in each of the regions. And Fig. 12 shows the corresponding material weights. These add up to a total of 323 kg (710 lb). This weight is for a radial reflector composition of 35 percent molybdenum alloy (TZM) which would be used as an outer cover to can the 55 percent tantalum beryllide.

CONCLUDING REMARKS

A preliminary cost estimate for the reactor described in Ref. 7 was made by Howard Yacobucci of this Center. It totaled to about four million dollars including the countrol drum actuators, but it was for a 22.8 in. diameter reactor with 247 fuel elements. This reactor would have only about one fourth the number of fuel elements, and a 14 in. diameter pressure vessel rather than a 22.8 in. diameter T-111 pressure vessel. Both of these should decrease the cost. Also, there is now several hundred kilograms of U^{233} with about 7 ppm U^{232} in storage. There is no present use for this fuel, and there is talk of burning it in the Savannah reactors. But if this is done it will be of no more value than U^{235}. Thus a four million dollar cost for this reactor should be a gross overestimate. But if we use it anyway, and assume a 30 percent efficiency for the Brayton cycle, the cost per kilowatt of electricity would be

$$\frac{\$4\times10^{6}}{150\ \text{kwe}} = \frac{\$2.7\times10^{4}}{\text{kwe}}$$

which is a large reduction over the costs given in Fig. 1.

Figure 13 shows a specific weight comparison of this reactor with that of the presently planned 5 kwe zirconium hydride. It will have a thermal power capability of 80 kw at a weight of 218 kg (477 lb) for a specific reactor weight of 6 lb/kwth. This specific weight should go down for a higher power version of the zirconium hydride reactor, but at this time it is not known by how much. For 450 kilowatts of heat from this reactor at a weight of 323 kg (710 lb) the specific reactor weight would be 1.6 lb/kwth, which at a lithium outlet temperature of 1400° K should lead to a very competitive system.

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SYSTEM	COST, $/KWE	SYSTEM WEIGHT, #/KWE	RADIATOR AREA, FT^2/KWE
SOLAR CELL BATTERY	$0.8 - 1.0 \times 10^6$	50 - 600	60 - 300
RADIOACTIVE THERMOELECTRIC GENERATORS	$13 - 15 \times 10^6$	600 - 1200	
Zr Hx REACTOR - THERMOELECTRIC	$\sim 0.5 \times 10^6$	340 - ?	50

Figure 1. - Space electric power systems.

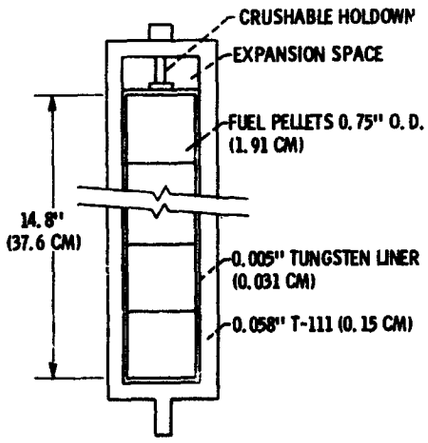

Figure 2. - Fuel element.

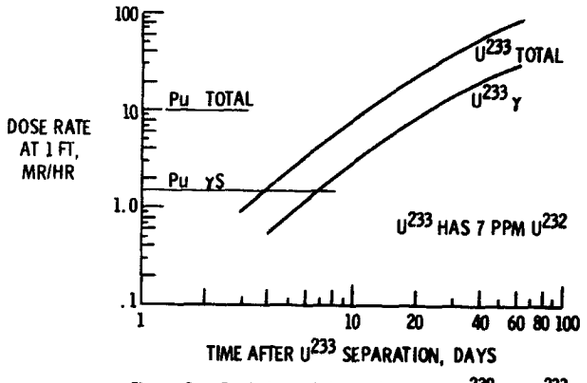

Figure 3. - Fuel element dose rates from Pu^{239} and U^{233}.

FISSION NUCLIDE	DELAYED NEUTRON FRACTION
U^{235}	0.0064
U^{233}	.0026
Pu^{239}	.0020

Figure 4. - Delayed neutron fractions for fissions from fast neutrons.

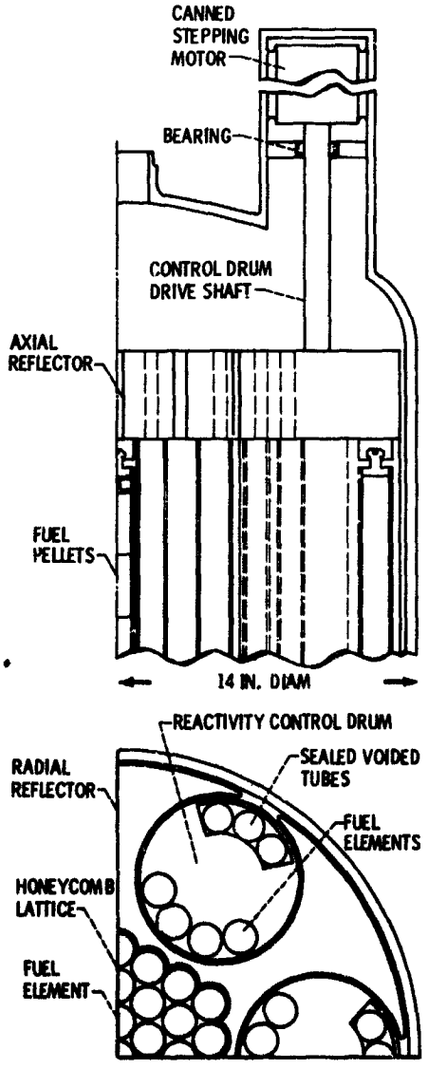

Figure 5. - Small space power reactor.

FUEL	REFLECTOR	FUEL FULL I_λ	FUEL FULL OUT[b]
$U^{233}N$	MOLYBDENUM	1.073	0.951
$U^{233}N$	TANTALUM BERYLLIDE (Ta_2Be_{17})	1.084	.951
$P^{c}_{U}N$	MOLYBDENUM	1.104	

[a]ALL CALCULATIONS INCLUDE A LITHIUM HYDRIDE SHIELD.
[b]ALL SIX DRUMS ROTATE IN THE SAME DIRECTION.
[c]Pu COMPOSITION IS 94.79% Pu^{239}, 4.9% Pu^{240}, 0.31% Pu^{241}.

Figure 6. - Calculated multiplication factors. (DOT - RΘ - S_3P_0 - 13 grp.)[a]

		%, Δk/k
TEMPERATURE DEFECT: (293 - 1480 K) OR (68^0 - 2200^0 F)		
CORE EXPANSION	-0.9	-1.7
Li^7 COOLANT EXPANSION	-.4	
DOPPLER (ESTIMATED)	-.4	
LIFETIME: 445 KWTH FOR 44,000 HR		
1.83 ATOM % OF U-233 DESTROYED	-1.2	-1.9
AXIAL FUEL SWELLING WITH FISSION	-.7	
PRODUCT BUILD UP		
CONTINGENCY:		.5
CALCULATIONAL BIAS		4.1
		3.0
TOTAL CALC. REG.		7.1

Figure 7. - Reactivity requirements.

	%, Δk/k
OPERATING	
445 KWTH AT 2200° F FOR 44,000 EFPH	4.1
SHUTDOWN	
K_{eff} = 0.99 WITH 2 ADJACENT CONTROL DRUMS STUCK IN THE MOST REACTIVE POSITION	4.6
TOTAL	8.7

Figure 8. - Reactivity control requirements.

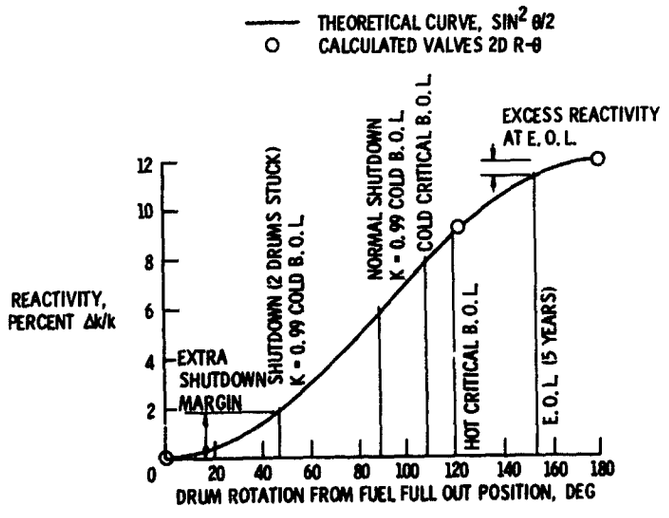

Figure 9. - Reactivity control curve.

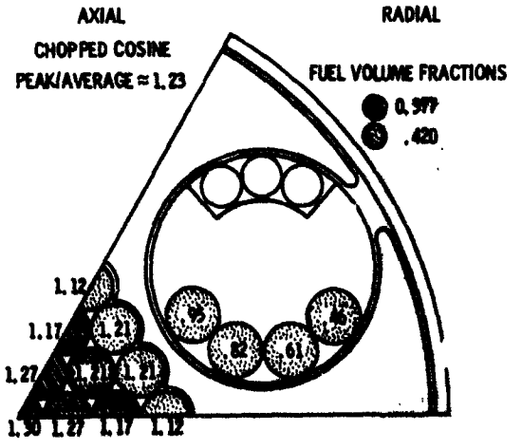

Figure 10. - Power distributions.

MATERIAL	DENSITY, G/CM^3	VOLUME FRACTION IN REGION					
		ZONE 1 FUEL CELLS	ZONE 2 FUEL CELLS	DRUM FUEL CELLS	REFLECTOR	EMPTY TUBE SEGMENT	PRESSURE VESSEL
REGION AREAS (CM^2)	-------	76.68	72.60	96.84	603.96	73.20	69.72
URANIUM[a] NITRIDE	14.2	.377	.420	.420	--------	-------	-----
T-111[b]	16.72	.244	.244	.244	--------	.2156	1.0
LITHIUM 7	.516[d]	.252	.252	.159	.0729	-------	-----
LITHIUM 6 HYDRIDE[e]	.8	------	------	------	--------	-------	-----
MOLYBDENUM[c]	10.2	------	------	.093	.9086	-------	-----
TUNGSTEN	19.3	.015	.015	.015	--------	-------	-----
TANTALUM BERYLLIDE (Ta_2Be_{17})[c]	5.05	------	------	------	.9086	-------	-----

[a] 0.982 Wt% U233, 0.011 Wt% U234, 0.007 Wt% U238.

[b] 0.892 Wt% Ta, 0.085 Wt% W, 0.023 Wt% Hf.

[c] EITHER Mo OR Ta_2Be_{17} USED, NOT BOTH AT SAME TIME, FOR REFLECTOR.

[d] DENSITY AT 460 K.

Figure 11. - Material specifications in each region.

MATERIAL	REGION						
	FUEL ZONE 1	FUEL ZONE 2	DRUM FUEL	RADIAL REFLECTOR	EMPTY TUBES	AXIAL REFLECTOR	PRESSURE VESSEL
VOLUME (LITERS)	2.88	2.73	3.64	22.71	2.75	2.53	2.62
URANIUM NITRIDE	15.64	16.28	21.71				
T-111	11.76	11.14	14.86		10.5		43.8
LITHIUM 7	.37	.35	.29	.86		.09	
TUNGSTEN	.83	.79	1.06				
MOLYBDENUM				84.18		23.73	
TANTALUM BERYLLIDE	(Ta_2Be_{17})		1.71	62.52			
	28.60	28.56	39.63	147.56	10.5	23.82	43.8

GRAND TOTAL = 323 KG or 710 lbs.

NOTES:

1. CORE LENGTH = 37.6 CM.
2. RADIAL REFLECTOR COMPOSITION: 35% Mo, 55% Ta_2Be_{17}, 7% Li^7.
3. AXIAL REFLECTOR COMPOSITION: 92% Mo, 7% Li^7.

Figure 12. - Reactor weights (kg).

	LOW POWER ZrHx	HIGH POWER ZrHx	SMALL, FAST SPECTRUM
POWER CAPABILITY (THERMAL KW)	80	400	450
REACTOR WEIGHT (LB)	477	?	710
SPECIFIC REACTOR WEIGHT (LB/KWTH)	6.0	?	1.6

Figure 13. - Specific reactor weight comparison.